Gravity currents with convective mixing: high-resolution numerical simulations

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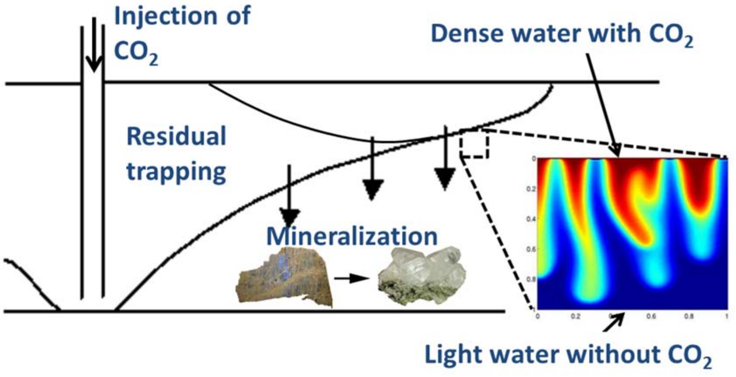
Trapping mechanisms

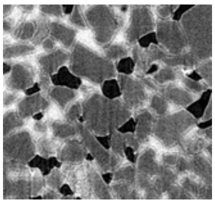


CO_2 plumes can migrate for long times after injection stops but are trapped by:

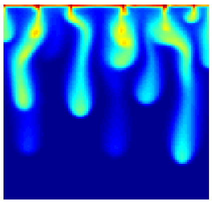
- Structural trapping
- Residual trapping
- Dissolution trapping
- Mineralization

Research questions and challenges

- What is the interplay between the migrating plume and convective mixing?
- How far does the plume migrate before it is fully trapped?
- How long does it take before the plume is trapped?
- What are the requirements for upscaled models?



2.2 mm



10 m

1 cm

Challenges for numerical solutions of plume migration with convection:

- Length scales: meters to tens of kilometers
- Time scales: days to tens of thousands of years
- -> The problem has been referred to as "impossible to solve"
- -> Simplified models have been presented
- -> There is a need for a reference solution

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Governing equations

Mass conservation equation for each component:

$$\frac{\partial}{\partial t}\left(\phi \sum_{p=1}^{n_p} x_{cp}\rho_p S_p\right) + \nabla \sum_{p=1}^{n_p}\left(x_{cp}\rho_p \mathbf{U}_p + s_p \mathbf{J}_{cp}\right) = 0$$

where $p = w, n$ (phases) and

$$\mathbf{U}_p = k\frac{k_{rp}}{\mu_p}\left(P_c + \overline{\rho_p} g \nabla d\right), \qquad \mathbf{J}_{cp} = -\rho_p D_{cp} \nabla x_{cp}$$

$$k_{rw} = S_e^4, \qquad k_{rn} = 0.4 \cdot (1 - S_e^2)(1 - S_e)^2 - C$$

$$S_e = \frac{S_w - S_{wr}}{1 - S_{wr}}, \quad P_c = \frac{0.2}{\sqrt{S_e}}, \quad x_{cn} = K_c x_{cw}, \ \rho_w = \rho^o + \Delta\rho x_{gw}$$

ϕ – porosity	s_p – phase saturation	x_{cp} – phase concentration
ρ_p – phase density	K_c – equilibrium constants	D_{cp} – diffusion coefficient

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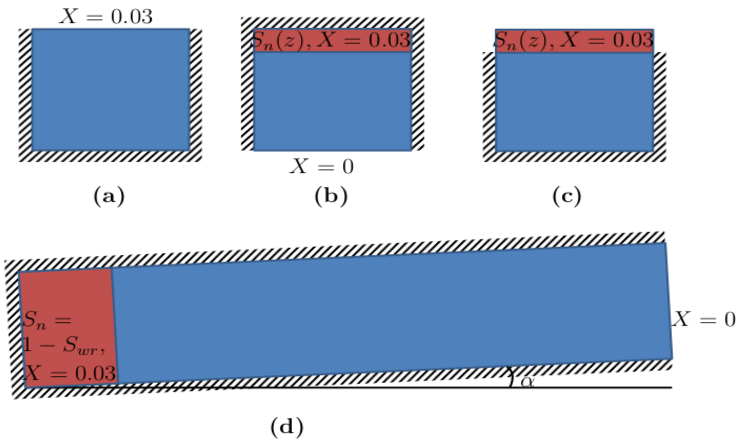
Model problems



$K = 100\ mD,\ S_{wr} = S_{nr} = 0.2,\ D_{cp} = 2 \cdot 10^{-9}\frac{m^2}{s},\ \ \phi = 0.15$

$\rho_n = 733\frac{kg}{m^3},\ {\rho_w}^0 = 1099\frac{kg}{m^3},\ \ \mu_n = 0.06\ cp,\ \ \ \mu_w = 0.51\ cp$

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Modeling framework: AD-GPRS

Features	Implemented in current release
Formulations	Natural and Molar, full capability for black-oil model, unified restart, tie-line-based formulation
Physical models	Black-oil, fully EoS two- and three-phase, thermal, external libraries, K-value formulation, solid phases
Properties	AD-EoS, AD-PVT, external libraries, hybrid approach
Space approx.	Cartesian, unstructured, MPFA, nonlinear MPFA
Time approx.	FIM, AIM+, Sequential Implicit
Geomechanics	Fully and sequentially coupled, thermal stresses
Chemistry	Kinetics and equilibrium, precipitation and dissolution
Speed	Active window, shared memory parallel (OpenMP, GPU)

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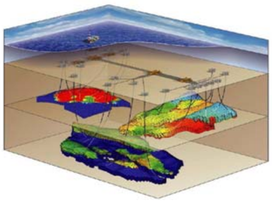
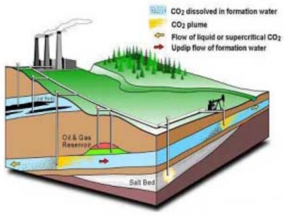
Target models for AD-GPRS

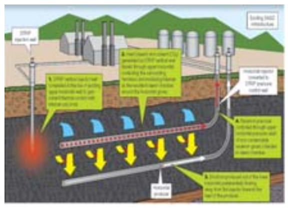
Petroleum Reservoirs



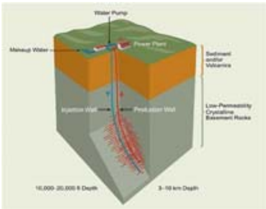
CO_2 storage in saline aquifers



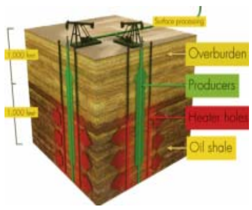
Enhanced Steam Injection



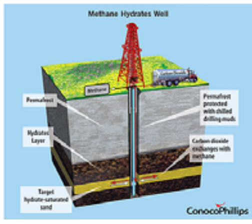
Enhanced Geothermal



Shale-gas/oil and oil-shales



Methane Hydrates



(images from DTU, ETH Zurich, RII, MIT, Shell, Conoco-Phillips)

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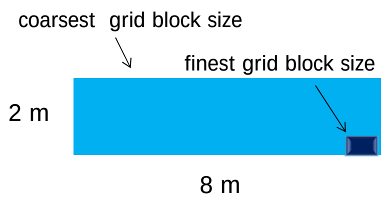
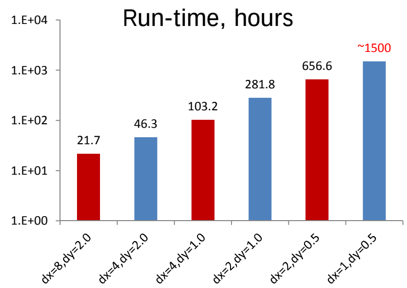
Numerical approach

- Finite Volume Two Point Flux Approximation on Cartesian grid
- Fully Implicit approximation in time
- Natural variables nonlinear formulation with Appleyard chop
- Constrained Pressure Residual preconditioner for GMRES solver
- Shared-memory run on Dual E5-2660 Intel CPU with 8 cores (16 threads) at 2.2 GHz

Grid resolutions (sloped aquifer):
62,500– 2,000,000 cells





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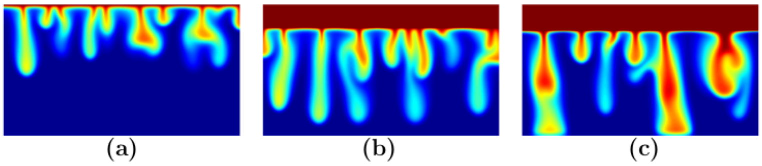
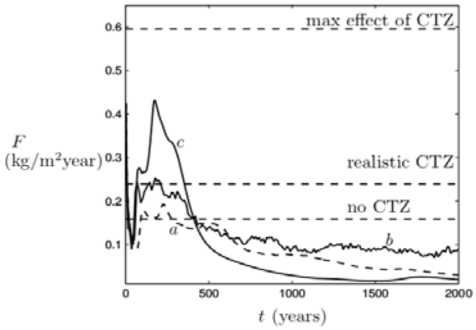
Small domains

Single-phase brine   Transient CTZ   Stagnant CTZ

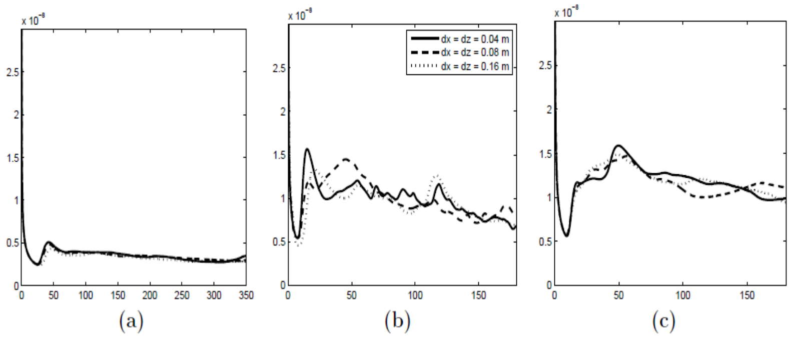




- The dissolution rate F is increased with the Capillary Transition Zone (CTZ)
- Transient CTZ has F=0.24 kg/m^2 year, as in [2]
- Diffusion at the bottom enhances F at late times

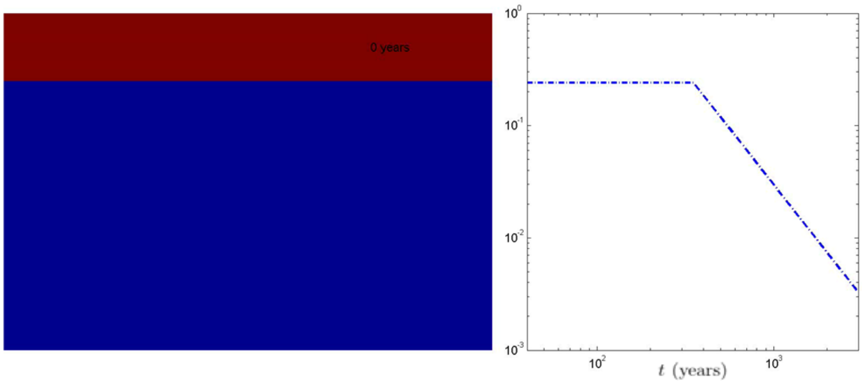
[2] Elenius et al., 2014.

Convergence on a small scale



CO2 dissolution rate (kg/m2) for the a) single-phase, b) transient CTZ, and c) stagnant CTZ.

Small domains – late time scaling



- When the fingers have reached the aquifer bottom and the CO_2 concentration in the upwelling water is enhanced ($t=t_{peel}$), the rate is reduced.
- A simplified model, similar to [3], (blue dashed line) uses a constant rate until t_{peel}, and then a rate proportional to $1/t^2$.
- A different scaling should be used if diffusion is allowed through the bottom of the aquifer.

[3] Slim 2014.

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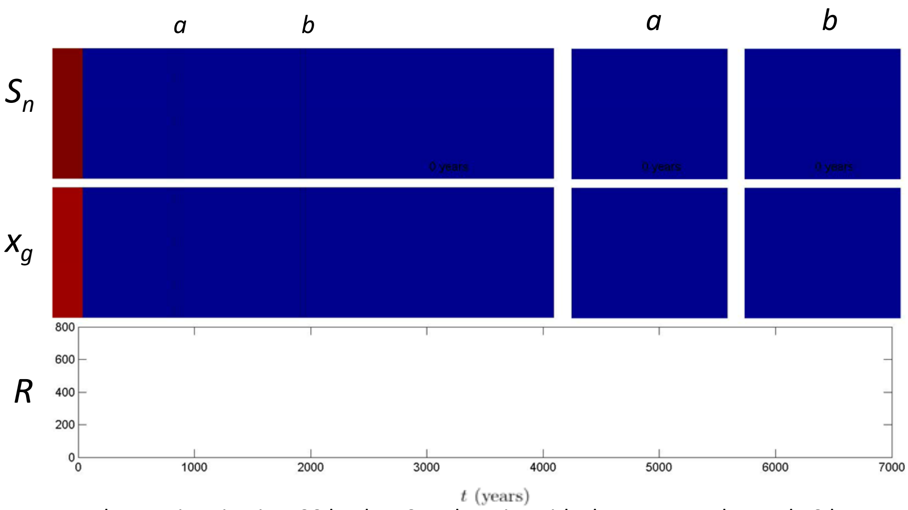
Sloping aquifer – plume and convection



- Plume migration in a 20 km by 50 m domain, with close-ups at 5 km and 10 km.
- Convection appears under the plume, but the brine is not saturated with CO2.

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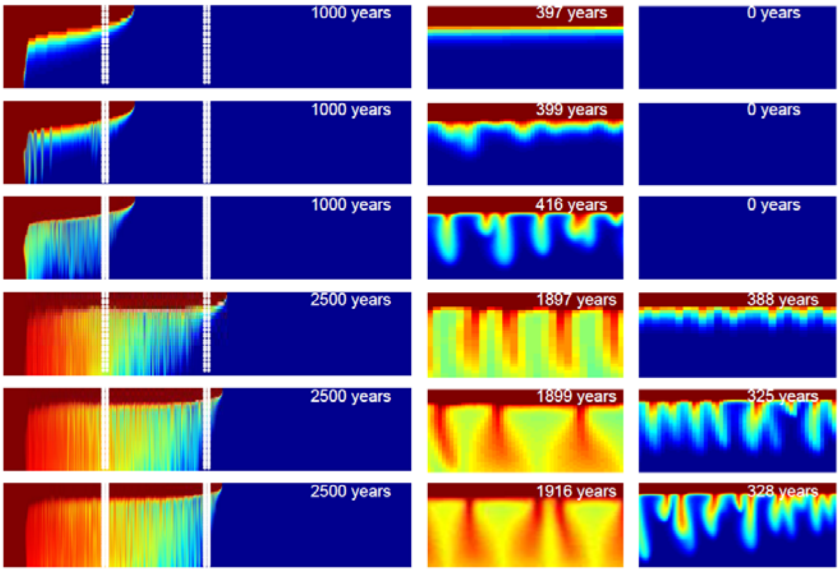
Converged solution



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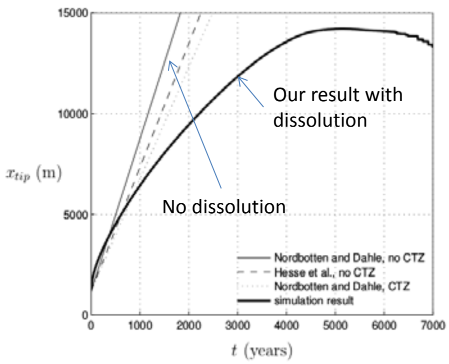
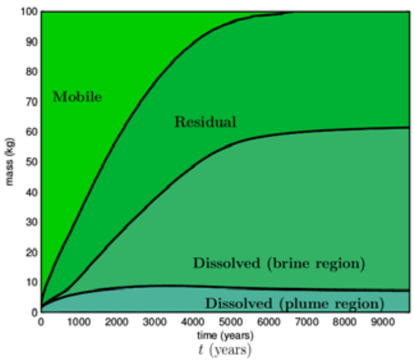
Tip position and distribution of mass





- The plume travels for 5000 years, reaching a final distance of 14 km up-dip from the injection site. The plume speed is significantly reduced by dissolution.
- It takes another 2000 years before the CO_2 is completely trapped as residual (40%) and dissolved (60%) CO_2.

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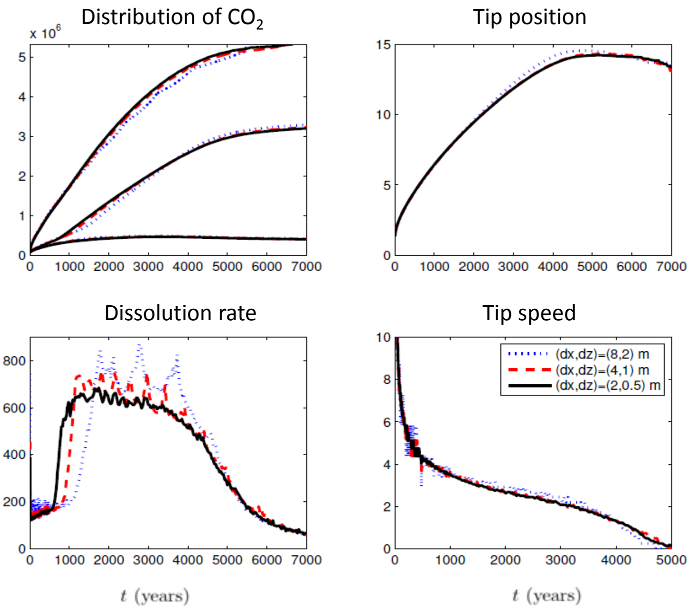
Convergence of different parameters



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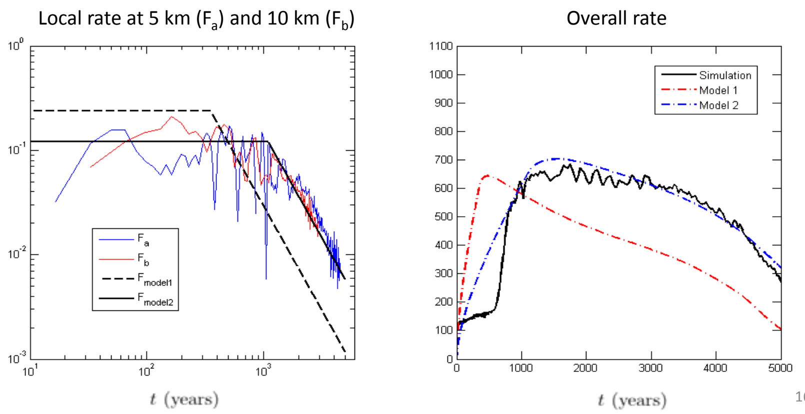
Convection under the plume

Simple analytical model for dissolution rate compared with simulation:

$F(x,t) = F_{max}$ if $t_{exp}(x,t) < t_{peel}$, else $F(x,t) = F_{max}(t_{peel}/t_{exp}(x,t))^2$

- Model 1 (small scale simulation): F_{max} = 0.24 kg/m²/year, t_{peel} = 350 years
- Model 2 (fitted to large scale): F_{max} = 0.12 kg/m²/year, t_{peel} = 1100 years



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Conclusions

- For the first time, a converged solution was obtained for the tip propagation of a two-phase gravity current with convective mixing!
- The plume travels for 5000 years, reaching a final distance of 14 km up-dip from the injection site
- Dissolution causes a significant reduction of the plume speed
- The dissolution rate follows a $1/t^2$ scaling at late times
- A simple fitted analytical dissolution model can reproduce a dissolution process quite accurately

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M.T. Elenius, D.V. Voskov, H.A. Tchelepi.
Interactions between gravity currents and convective mixing.

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